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Introduced Species and the 21st Century Floras

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Major causes of damage to the environment include habitat destruction, habitat fragmentation, overharvesting of plants and animals, pollution and invasion by alien species. Although the first four causes have been recognized for many years, invasion by alien species has only recently been acknowledged and accepted as a serious threat to natural environments and to human health and welfare on a worldwide scale. In North America, introduced species range from the well-known, macroscopic examples, such as purple loosestrife (*Lythrum salicaria* L.) to microscopic, less well-known aliens, such as cholera (*Vibrio cholerae*). Estimates of the costs to society in reduced agricultural productivity, threats to human health and in direct expenditures for the control of introduced species are discussed. Suggestions for a modern method of preparing floras to allow for monitoring the introduction and predicting the spread of alien plant species is presented. Interactive identifications tools, geographic information systems (GIS) and a database of herbarium specimens and their associated label data combined with digital images of the plants for large geographic regions, such as for a country or a continent, can provide the means to readily identify the plants from throughout the area, but also can provide a powerful means for monitoring plant introductions and predicting their potential to spread into native habitats.

Key words: alien species, database, environment, flora, introduced species

In his review of the BBC television series, *State of the Planet*, by David Attenborough and the British Broadcasting Corporation (BBC) for winter of the year 2000, Andrew Sugden (2000) notes that Attenborough identifies five major causes of damage to the environment: 1) habitat destruction, 2) habitat fragmentation, 3) overharvesting, 4) pollution and 5) invasions by alien species. (Also presented on the BBC *State of the Planet* web site http://www.bbc.co.uk/nature/earth/state_planet/20 December 2000). Scientists have generally been aware of the first four of these often dramatic and often easily observable threats for many years. Habitat destruction is the result of logging activities and the conversion of natural habitats to habitats suitable for agriculture, industry and commerce and human habitations. Fragmentation is usually the result of habitat destruction and reduces large landscapes to small patches or "islands" only a fraction of their original size. Overharvesting easily can be seen when vast areas of both tropical and temperate forests are cleared, but is not obvious to the casual observer when the overharvesting is concentrated on the gathering of particular, often herbaceous, species of plants for medicinal purposes. In North America, ginseng, *Panax quinquefolius* L. and Goldenseal, *Hydrastis canadensis* fall into the latter category, and in China, where

more native plants are utilized for health purposes than perhaps in any other country, a very large number of species, primarily woodland species, have been seriously decimated. Recently, as new roads and airports have been and continue to be built, once remote and inaccessible areas are being opened to an increasing number of tourists, travelers and business people. The local people in these once remote areas have taken advantage of this influx of potential customers to tout and market vast quantities of locally collected wild plants as health foods and medicine. Certain species of *Saussurea*, many tuber bearing and rhizomatous plants and many parasitic plants, such as members of the Orobanchaceae, are being locally wiped out because of this activity and increased harvesting.

After many years of accepting the belief that black skies signaled jobs and prosperity, the effects of pollution and its threat to the environment became a major concern in the 1960s and 1970s. It was realized that many streams and rivers had been killed or were dying because of the of the toxic wastes and chemicals being poured into them and that forests were dying because of acid rain resulting from unfiltered emissions from power plants and heavy industry. In America, the first Earth Day in 1970 marked a major turning point and made everyone realize the serious threat to health and the environment caused by bad air and water. The late 1960s and early 1970s marked a period of turmoil, conflict and divisiveness in the United States over topics ranging from civil rights to the war in Vietnam. Nevertheless, the first Earth Day brought all the various groups together behind the common goal of cleaning up the environment.

The awareness and concern of the threat to our environment by the introduction, establishment and spread of non-native plants, animals and microorganisms is much more recent, although we have been aware of specific, often spectacular instances of invasions by alien species for many years. Among the better known examples are the effects of the introduction of European rabbits (*Oryctolagus cuniculus*) and American prickly pear cactus (*Opuntia*, Cactaceae) into Australia, the various species of European deer into New Zealand, the introduction of the Norway rat worldwide, the destruction to local plants by the introduction of domestic and feral goats and the effect on populations of small mammals and birds by domestic and feral cats when they are brought into areas where they were previously absent. More recently, the introduction of the Brown Tree Snake from Papua New Guinea to Guam, where it has wiped out 12 of the 14 local bird species and drastically reduced populations of small mammals and lizards, has gained worldwide attention. As a small benefit, the snakes have also reduced the island's population of rats, which are themselves alien to the island. Despite these classic examples of the damage and destruction that non-native species can cause when introduced into areas where they have no natural enemies to control them, very little has been done to monitor the introduction and spread of the world's biota.

Pimentel et al. (1999) report that the environmental damage and losses caused by nonindigenous species in the United States amounts to more that $138 billion per year. They estimate that 42 percent of the species on the U.S. Threatened and Endangered list are there because of the risk from nonindigenous species.

It is estimated that there are approximately 50,000 non-native species in the United States (Pimentel et al. 1999, Wolfenbarger and Phifer 2000), with more arriving constantly. Surprisingly, for such a large number there are relatively few that have become serious pests, although all have the potential when they arrive to take advantage of new habitats where their enemies are few or

nonexistent. Nevertheless, with the ease of worldwide travel the spread of organisms from one continent to another is not likely to slow in the coming years. Along with the ability to reach almost any place on earth within a single day comes the ability to transmit infectious diseases from one place to another so quickly that the carrier does not even have time to become aware of being infected. The appearance of the West Nile virus, or West Nile encephalitis, in New York city in 1999, where it killed many birds and seven of the sixty people who were infected, took everyone by surprise. The virus is carried by birds and transmitted to people by mosquitoes. Once the organism was identified and the life cycle became known, massive spraying with pesticides to control mosquito populations was initiated, but that in itself resulted in heated debate. Some argued that since the West Nile virus was a tropical disease it would disappear during the cold New York winter when mosquitoes died off and it was unnecessary to expose populated areas and beneficial insects to the dangerous, indiscriminate and widespread use of pesticides. Trapping in New York's sewer system, however, revealed that mosquitoes were not only able to survive in northern climates, but also to harbor the virus through the winter. In the year 2000 the virus showed up in a wider area, first to the northeast in the New England states, and then as far south as Virginia. It seems likely that migrating birds will soon carry it throughout the Americas.

A recent article in Science (Ruiz et al. 2000) has identified sea water used as ballast in commercial ships as another potential source of harmful alien invaders. Ships have historically used ballast of some sort for centuries. As can be seen on herbarium labels and in floras, ship's ballast has been the source of introduction of a number of alien plants into the United States. Some of these invaders, such as *Parietaria judaica* L., have never spread beyond their point of introduction in North America (Boufford 1997), but have been so closely associated with ports since they were first collected that there is little doubt as to their origin. Others, such as *Urtica urens* L., finding conditions favorable throughout their new-found home, and having seeds that are easily transported, have spread widely beyond seaports where they almost surely first appeared.

Ruiz et al. (2000), however, identify a potentially more serious threat to human health. In sea water used as ballast in ships of foreign origin arriving in Chesapeake Bay on the east coast of the United States they found significant concentrations of plankton, bacteria, virus-like particles and, most significantly, two infectious strains, O1 and O139, of *Vibrio cholerae*, both of which cause human epidemic cholera. They found *V. cholerae* in all samples tested and both serotypes were found in ballast water of 93 % of the ships. They point out that a novel genotype arriving in ballast may favor its establishment in a new site. They also predict that coastal ecosystems are frequently invaded by microorganisms in far great concentrations than by other taxonomic groups by 6-8 orders of magnitude. They further predict that the probability of successful invasion should increase with inoculation concentration and point out that even with the current awareness of the threat posed by introduced pathogens and emergent diseases, the extent and effect of ballast water as a transport medium is unknown.

Another recent discovery in the United States is the parasite *Leishmania infantum*, which sickens over half a million people each year in South America, India and the Mediterranean region. So far, the parasite has been restricted to hunting dogs, but has been found in 21 states of the United States and in Ontario in Canada (Enserinck 2000). The disease had been found sporadically in the past in dogs brought back to the United

States from military bases in the Mediterranean region, but recently it was discovered in foxhounds in Millbrook, New York. The dogs suffered from bleeding, weight and hair loss, seizures and kidney failure. Subsequent testing of 11,000 dogs in the eastern United States showed that 12 percent of them contained antibodies for *Leishmania.* Although no instances of Leishmaniasis have been discovered in humans yet, the threat seems possible. Where it is endemic, Leishmaniasis is spread to humans by sandflies of the family Phlebotomidae. It can infect bone marrow and the liver and spleen and occasionally be fatal. The question currently puzzling those trying to understand the spread of the disease in dogs in the United States is where did it come from and how was it able to spread so widely. Again, with the ease of international travel it should not be surprising for diseases of distant lands to suddenly appear in unsuspected places.

The control of introduced species can also be expensive and use up resources that could be utilized better in other ways. For years the United States has spent millions of dollars annually to control the spread and increase in population size of the fire ant, *Solenopsis invicta* Buren. It is believed that fire ants entered the United States in the port of Mobile, Alabama, in the early 1920s or early 1930s on ships arriving from Argentina. The fire ant is noted for the large mounds it builds, for the aggressiveness of the ants when the mounds are disturbed and for their ferociousness. Unlike native American species of ants, the fire ants immediately emerge en-masse and attack whatever comes in contact with their mound. The bite is extremely painful, and when dozens or even hundreds are biting at the same time, the sensation is a burning, hence the source of the common name. Besides the annoyance to humans, fire ants are also injurious to livestock and can easily overwhelm and kill smaller animals. They are particularly harmful to endangered species such as gopher tortoise hatchlings, the young of salt marsh rabbits, sea turtles, Florida grasshopper sparrows and Stock Island tree snails. There are only 300 green sea turtles in the world, and fire ants often attack and kill or blind the hatchlings when they cross the fire ant mounds on the way to the sea. The fire ants will also attack the hatchlings as a source of food for the colony. Besides attacking small animals and birds directly, fire ants probably reduce population sizes of small insectivorous animals by out competing them for food.

Since its introduction the fire ant has also changed its patterns of behavior. Dr. Edward Wilson, a renowned expert of ant taxonomy and behavior, has noted that colonies of fire ants in their native Argentina have a single queen per colony and that when colonies come in contact with each other they engage in warfare until one colony is wiped out. In the United States, however, instead of engaging in warfare, the ants have learned to merge colonies and house multiple queens, thereby enlarging colony size and allowing for more closely spaced colonies. The fire ant does, however, battle with native species of ants and has reduced native ant populations throughout its area of colonization, which now stands at 121.4 million hectares in the southern United States and is still slowly expanding. Most recently it has moved beyond the southern United States and Puerto Rico into New Mexico and California. Also, in colonies in the United States with a single queen, the workers will adopt a new queen if the original queen dies, which therefore makes it difficult to eliminate a colony by attacking and killing the queen as in other social insects.

Efforts to control the spread and population size of fire ants have relied almost solely on the use of pesticides, but recently there has been a major push to identify, test and introduce biological controls. Among those

most promising are two microorganisms that attack fire ant colonies and cause disease. One of these, *Thelohania solenopsae* Knell, Allen & Hazard, is probably introduced to the queen by workers when they provide her with food. The infection causes her to lose weight and to lay fewer eggs, all of which are infected, thereby weakening the entire colony. *Thelohania solenopsae* infections usually result in the death of the colony in 9 to 18 months, but studies have shown them to be reduced in size after three months. Surprisingly, *Thelohania solenopsae* was found to be already present in Florida, Mississippi and Texas. United States Department of Agriculture-Agricultural Research Scientists in Gainesville, Florida, further released the pathogen in Florida in 1998 and within two years they found that it had already infested 75 percent of the fire ant colonies in the state.

The same scientists are also studying and testing a more virulent microorganism of the genus *Vairimorpha*. They found that by combining it with *Thelohania* it kills colonies of fire ants in two to six weeks. *Vairimorpha* is much rarer in nature, and therefore more difficult to obtain, infecting only about one percent of fire ant nests in South America, and it is more difficult to keep alive.

Another introduced natural control of fire ants is a small phorid fly from Brazil, *Pseudacteon tricuspus*, which appears to prey solely on fire ants and no other species. *Pseudacteon* hovers over fire ant mounds and rapidly flies in to lay an egg on any fire ant it sees. The fly pierces the cuticle of the fire ants abdomen to lay the egg. The developing larva moves into the ant's head and at maturity it releases a hormone that causes the ant's head to fall off. The fly pupates in the safety of the hard, detached head. A single fly lays a hundred or more eggs, so can attack many members of an ant colony. Tests have shown that the fly does not attack other species of ants. Thousands of flies were released in central Florida in 1997 and surveys have found that they have survived, indicating that they have already gone through several generations. Since then, they have also been released in the states of Alabama, Arkansas and Oklahoma and it will be a few years before a judgement can be made on their success.

The promise of biological controls for the control of introduced pests, however, is never a guaranteed solution to controlling invasive species. Extensive tests under controlled conditions must be carried out to insure that the pathogen does not develop a preference for native species. The introduction of *Compsilura concinnata* (Meigen) (Diptera: Tachinidae) to control the gypsy moth, *Lymantria dispar* (L.), is one particular example where results did not live up to expectations. *Compsilura concinnata* was one of more than 45 species of natural enemies introduced over a period of more than 50 years, beginning in 1906, for the control of the gypsy moth. Unfortunately, *C. concinnata*, a European native, is indiscriminate in its choice of prey and does not restrict itself to gypsy moths. It has now been reared from more than 200 different host species in the United States. Some of them, such as the forest tent caterpillar, are also pests, but many are non-pest species of butterflies in the Nymphalidae (brushfooted butterflies) and large showy moths in the Saturniidae, including the Cecropia moth, *Hyalophora cecropia* (L.) (Pemberton and Strong 2000, Mahr 2000).

The gypsy moth, *Lymantria dispar* (L.), was accidentally introduced near Boston, Massachusetts, in the northeastern United States by E. Leopold Trouvelot. The moths were brought to the United States in 1869 to breed with silk worm moths in hopes of establishing a silk industry near Boston. Although the silk industry was never a success, the gypsy moths in their new-found home were. About 10 years after their

introduction, the first outbreaks began in Trouvelot's neighborhood and in 1890 the State and Federal Government began their attempts to eradicate the gypsy moth. These attempts have failed and the range of the gypsy moth has continued to expand steadily beyond its point of introduction and now has been found far from the northeastern states in western Canada and in a number of the western states of the United States. The success of the gypsy moth, without doubt, has been related to its ability to utilize as food the leaves of more than 100 (some reports of 300 to 500) species of primarily woody plants, besides its favorite foods of *Quercus* and *Populus*, in the United States and southeastern Canada. Attempts to control the spread of gypsy moth and to eradicate it where it has become established are continuing and in recent years in New England the evidence of gypsy moth damage has not been conspicuous. In the early 1980s, however, complete defoliation was extensive in the forests of the northeastern United States. In July of 1981 there was nearly 100 percent defoliation in more than 4.8 million hectares of forests ranging from Pennsylvania to central New England. Since then, pathogens have apparently kept massive infestations in check, but have not eliminated the gypsy moth or halted its spread westward. An excellent web site for information on spread and control of gypsy moths is at www.fs.fed.us/ne/morgantown/4557/gmoth/.

The starling (*Sturnus vulgaris* L.) was also brought into America intentionally from Europe in the late 1800s by Eugene Schieffelin, who also lived near Boston. He wished to increase the popularity of William Shakespeare by introducing to America all the birds mentioned in Shakespeare's writing's. Because of their habit of aggregating in large flocks, starling's are damaging to the environment in a number of ways, but particularly by taking over nesting sites preferred by native birds, and by their feeding and roosting habits, which consists mainly of fouling and food removal (Anonymous 2000). These omnivorous birds no doubt take food that would have been used by native species. In rural roosts, which are usually in dense thickets, the combination of large quantities of starling guano and the weight of birds on branches can eventually kill the trees. In cities, droppings foul the pavement, disfigure buildings and monuments erode stonework, and probably spread disease. Starlings occasionally take grain from winter cereal sowings, and at intensive animal husbandry units they may take a considerable proportion of animal feed. In cherry orchards trees may be stripped by birds before the pickers can collect the fruit. Starlings, the common pigeon (*Columba livia*), another pest that fouls buildings, pavements and park land, contaminates stored food and transmits diseases, and the English sparrow (*Passer domesticus*), all introductions, appear to be with us to stay.

The taxonomic groups and regions with which I am most familiar are the plants, and particularly the plants of eastern North America and temperate Asia. Until recently, alien and invasive plant species in North America have been considered mostly a nuisance or a casual topic of conversation and for the most part have not been seen as a serious environmental threat or received much attention until about the past decade. Even so, with few exceptions, most of the current focus in North America, as with wildlife issues worldwide in general, has been on animal species, such as the fire ant, killer bees and zebra mussels. Millions of federal and state dollars has been spent to investigate and to control these animal aliens, but far smaller amounts have been allocated for the control and elimination of introduced and invasive plant species, many of which have spread farther and faster than could have been predicted. Almost certainly, more money has been spent by government

agencies for the introduction, propagation and planting of many of the species that are now serious pests than has been spent on monitoring their behavior and controlling their spread subsequent to their introduction.

It is now estimated that about 5,000 non-indigenous plant species are naturalized in the United States (Morse et al. 1995), or slightly more than 29 percent of the approximately 17,000 plant species in the flora (Morin 1995). Naturalized means that they form a natural part of the flora and are reproducing on their own without the intervention of humans. Crop plants such as the tomato (*Solanum lycopersicum* L.), corn, or maize, (*Zea maize* L.), wheat (*Triticum aestivum* L.) and the potato (*Solanum tuberosum* L.) are sometimes found growing outside of cultivation, but none are able to persist or to propagate on their own and so are not considered to be naturalized. In cultivated plants, forsythia (*Forsythia* spp.) and lilac (*Syringa* spp.) often persist around old home sites or near dumps where they were discarded, but are not reproducing on their own despite their frequency and abundance in cultivation. In fact, forsythia rarely sets fruit in cultivation despite abundant flowers.

In the six New England states of the northeastern United States the number of introduced plants for each state has been tallied by Mehrhoff (2000). The overall totals for New England based on Seymour's (1969) *Flora of New England* were 1995 native species and 887 introduced species, or 31 % of the flora being introduced. Seymour's *Flora* was compiled almost entirely on the basis of herbarium specimens collected over the previous century and a half and housed in the herbaria of the New England states. More recent statistics for four of the six New England states, based on extensive field studies and more recent herbarium work, present a somewhat different picture, particularly for the states investigated most thoroughly. Connecticut figures, from Dowhan (1979), show 2625 species in the flora, of which 35% are introduced. The state of Maine (Campbell et al. 1995) has 1469 native species and 634, or 30 % introduced. Rhode Island, the smallest state in the United States, has 1226 native species and 392, or 24 %, introduced (Gould et al. 1998). Most surprisingly, however, is Massachusetts, which floristically is probably the most thoroughly studied state, with 1538 native species and 1276, or 45 %, non-native species.

Introduced plants appear to have come in two main waves to the Americas, the first from Europe over a period of about 400 years from 1500 to 1900, and the second from Asia since the last part of the 1800s and early 1900s. In a talk presented on the flora of New England to the Massachusetts Horticultural Society at the turn of the last century, Fernald (1905) reported the number of non-indigenous plants in the New England flora at that time to be about 600 species . All of them were European in origin, despite the fact that many Asian plants had been brought into cultivation by then (Rehder 1936, Mehrhoff 2000). In another talk 34 years later to the Franklin Society (Fernald 1940) the focus of attention was on the threat to rare plants posed by plants that had escaped from cultivation. Mehrhoff (2000) surmises that the new threat to native plants was coming from plants introduced from Asia. There is good reason to believe that supposition to be correct. Introduced plants from Europe prefer open areas, such as cleared land, roadsides and pastures. In eastern North America the activities of the European settlers provided ideal habitat for many of the plants they brought with them to provide food for themselves and their livestock and for ornamental purposes. The settlers first set about clearing the land for farming. Forests that at one time spread unbroken from the Atlantic Ocean to the Mississippi River were cleared for settlements and to provide the building materials and fuel for the houses

themselves, and to open up grazing land for cattle and arable land for crops. Native plants, which had evolved under closed forest conditions, were unable to colonize these large expanses of newly opened land as rapidly as the Eurasian introductions, which had evolved in open environments and were preadapted to extensive cleared areas. Native herbaceous plants quickly fill in natural blowdowns in undisturbed forests, but are soon replaced by native woody plants as succession proceeds. Cleared areas are also eventually reclaimed by native plants and vegetation, but the extent and thoroughness of the clearing by the early settlers made succession a very long term process. Some cleared, vegetated, but non forested areas, such as roadsides, pastures, railroad rights of way, lawns, golf courses and public parks are permanent for as long as they are maintained. These cleared areas are made up almost entirely of non-native species, some, such as many of the forage grasses, introduced intentionally, but many others unintentionally. The European custom of maintaining lawns in North America has required the introduction of non-native grasses. The most common lawn grass in the eastern United States, despite its colloquial name of Kentucky Blue Grass, was introduced from Europe. Pasture lands are also made up of European introductions, such as various species of *Trifolium* and *Medicago* (Fabaceae), *Phleum*, *Dactylis*, *Bromus*, *Festuca*, *Arrhenatherum* (Poaceae), and many others. These plants have not restricted themselves to the pastures where they were planted, but are now thoroughly established in all cleared areas to a greater or lesser extent. Seeds of some weedy plants were unintentionally imported along with the seeds of desired species and they too occur with the plants they arrived with. Very few of these plants of European origin, however, invade natural, undisturbed native habitats to any significant extent.

Despite the large numbers of naturalized plants in North America, very few are considered to be pests and many are considered to be beneficial. Another important observation is that, with very few exceptions, introduced plants rarely become established in natural, undisturbed native habitats. Why is that some species easily become naturalized and invasive, yet other related species, even those in the same genus do not? Of all the cultivated roses in the eastern United States, *Rosa multiflora* Thunb. is the only one that has so far become thoroughly naturalized and invasive. The common sentiment now, however, appears to be that any introduced plant is a threat and should be monitored carefully. Realistically, the concern should be focused only on the most invasive species and those capable of replacing native vegetation.

Unfortunately, a few non-indigenous plants can completely overrun some types of native vegetation. *Centaurea solstitialis* now dominates over 4 million hectares of grasslands in northern California, resulting in the total loss of a once productive resource for grazing animals (Pimentel et al. 1999). There is further potential for *C. solstitialis* to colonize an additional 16 million hectares in California. *Bromus tectorum* occurs throughout most of the United States, but has had its most severe impact on steppe-desert plant and animal communities in the Great Basin of Idaho and Utah. *Bromus tectorum* is an annual grass that densely colonizes any open or partially open area. It completes its life cycle early in the season and by mid summer the parent plants have died and become dry and brown. Summer lightning storms frequently set the dead stalks ablaze and in an area where fires once occurred in a cycle of once every 60–110 years, the frequency of fire is now down to every three to five years. The fires are particularly damaging to shrubs and other plants that require several years to mature. Animals dependent on the original

vegetation for food or shelter have been greatly reduced or eliminated in areas where this grass has taken over. It is estimated that *Bromus tectorum*, which has long, stiff awns and is unpalatable to animals, now occurs as a monoculture on more than two million hectares of land in Idaho and Utah.

In the northeastern United States *Lythrum salicaria* is one of several species of introduced plants that has become a severe threat to wetlands by replacing nearly all natural vegetation and forming enormous monocultures. In addition to reducing populations of native plants by outcompeting them, it has also resulted in the reduction or elimination of populations of native animals such the rare bog turtle (*Clemmys muhlenbergii* (Schoepf)) and several species of ducks that depend on the native plants for food (Pimentel et al. 1999, Gaudet and Keddy 1988). *Lythrum salicaria* was introduced in the early 1800s as an ornamental plant, and perhaps also in ships' ballast (Thompson et al. 1997), and in fact is still being sold in the horticultural industry as an ornamental and as a nectar plant for honey production despite its notoriety as an aggressive destroyer of wetlands. It has been spreading at a rate of about 115,000 hectares per year and completely changes the composition of all wetlands where it becomes established. It is known from 40 of the 50 states in the United States and from all the southern provinces of Canada and has been designated a noxious weed in at least 19 states (Kartesz and Meacham 1999). Once established, *Lythrum* often occupies 100 percent of a site, thereby eliminating most vertebrate and invertebrate populations that were dependent on the native vegetation. Like many invasive plants, populations at first built up slowly, then suddenly exploded exponentially in the latter half of the 1900s, so its invasive potential was not realized until it was thoroughly established. An interesting web site at http://omega.cc.umb.edu/~conne/jennjim/lythrum.html shows the spread of *Lythrum* into the wild in Massachusetts over the period from 1860 to 1969. Once established, *Lythrum* is extremely difficult to eradicate. Cutting the plants back encourages the formation of new shoots from rhizomes. In addition, each plant produces a prodigious number of seeds–a single plant being capable of producing more than one million. Attempts to controls or eradicate *L. salicaria* by digging, pulling, flooding, burning and spraying with herbicides have been unsuccessful (Thompson et al. 1997) and the best hope appears to be in the identification of natural biological controls. Three host-specific beetles have been approved for use in Canada as biocontrol agents of purple loosestrife. One is a weevil (*Hylobius transversovittatus* Goeze) that attacks the root system and the other two are leaf-feeding beetles (*Galerucella calmariensis* L. and *G. pusilla* Duftschmid). When present in high densities these insects cause defoliation of mature plants, death of seedlings and destruction of flowering spikes or prevention of their formation. Successful introduction of the insects and control of *L. salicaria* have been recorded at a number of sites. A seed eating beetle, *Nanophyes marmoratus* (Goeze), has also been tested in the United States. Young adults feed on new leaves at the tips of branches, then later feed on the flowers and closed flower buds. Sixty to one hundred eggs are laid in the immature flower bud. Seed production in infested plants is reduced by 60 percent. There were two test sites releases in 1996. *Nanophyes marmoratus* is being propagated at Washington State University in Pullman to increase their numbers (Piper 1997).

Among the places under greatest threat from introduced plants and animals are those where endemic floras and faunas have evolved. Those areas are most often islands or unusual, isolated habitats with particular environmental conditions and unique vegetation types. Such places include the Cape

Province of South Africa, the California Floristic Province, the Mediterranean region and Australia, particularly southwestern Australia, the Galapagos Islands and Hawaiian Islands. The flora of Hawaii, is particularly threatened. Already there are more non-indigenous, naturalized species (1072) in the Hawaiian flora than there are indigenous and endemic species (1029), and that discrepancy will surely widen. George Staples (pers. comm.), who, with Derral Herbst, has been preparing a treatment of the plants cultivated in Hawaiian gardens (Staples and Herbst in press), estimates that there are more than 8,000 non-native species already present there. In addition to the alien species already naturalized in the Hawaiian Islands, Staples et al. (2000) have prepared a list of an additional 470 cultivated taxa of plants which already show weedy tendencies and could become invasive.

The global spread of microorganisms in ballast water of ships was discussed above, but prior to sea water being used as ballast, rocks and dirt were used (Mehrhoff 2000). After a long trip from a distant port the ballast would be unloaded on special ballast grounds or ballast piles near the ports before the valuable cargo was loaded aboard. It was noted quite early in the history of botanical exploration in the United States that unusual plants could be found growing about these sites. Some botanists have always taken delight in exploring those areas to find unusual plants or plants unknown to them and being the first to report their discoveries from distant lands (Smith 1867, Burk 1877, Martindale 1876, 1877, Brown 1878a, 1878b, 1879, 1880, 1881). Those investigations eventually spread to other sites where introduced plants might appear, such as in the vicinity of waste piles around textile mills. Many herbaria in the United States have unidentified specimens with the habitat given as "wool wastes" on the label (Collins 1901, Fletcher 1912, 1913, 1915, 19167, 1917, Weatherby 1924, 1932). Wool was imported from throughout the world, so the possibility of finding some truly unusual plants was great. Besides textile mills, other types of factories around which introduced plants and adventives were frequently found included a rubber plant in Waterbury, Connecticut, that processed reclaimed rubber from shoes (Blewitt 1911, 1912) and a glue factory in Danvers, Massachusetts, where *Lepidium latifolium* L. was discovered (Mehrhoff 2000).

Others botanists have taken to the railroads in search of adventives. Victor Mühlenbach first started his investigation in the railroad yards in his native Riga, Latvia (Mühlenbach 1985), then picked up his studies in St. Louis, Missouri, after moving to the United States after the second world war. Railroads also appear to have helped seminative plants expand their range. *Rudbeckia hirta* L., a plant native to the midwestern United States prairies and plains, is now common in old fields and cleared areas throughout the eastern United States. It is suspected to have moved eastward on the artificial 'prairies' created and maintained along the railroad's rights-of-way with further help by the trains themselves in transporting seeds. Mehrhoff (2000) notes that *R. hirta* had reached Philadelphia by 1826 and New England by 1855. Fernald (1905) also suspected that *Senecio jacobaea* L. reached Portland, Maine, from New Brunswick, Canada, by rail (Mehrhoff 2000).

Other native plants also have been able to expand their natural range by utilizing newly created environments that mimic their natural habitat. *Solidago sempervirens* L., colloquially called seaside goldenrod because of its once restricted occurrence in salt marshes along the immediate Atlantic coast, has now spread far inland along the margins of expressways and other highways in the New England region. The heavy use of salt on highways in the northeastern United States to

melt snow and ice and the salt run-off with melting snow and spring rains has apparently created conditions that either mimics the salt marsh habitat or reduces competition to the point where *S. sempervirens* is able to become established and thrive. Non-native plants, such as *Artemisia vulgaris* L., have also utilized the restricted artificial habitat of highway margins to spread far inland from the coastal areas where they first became established and naturalized.

Mullin et al. (2000) have outlined a number of recommendations for reducing the costs of invasive alien species. Prevention programs must be developed that identify potentially invasive species; laws must be passed and those who transport or offer for sale potentially invasive plants must be held accountable; introduced species must be screened to determine their likelihood of becoming invasive before being introduced for forage, revegetation, erosion control or horticulture; programs to educate the public and to make them aware of the monetary and biological costs must be developed; coordinated control programs must be established; research on the biology, ecology and control of invasive plants must be increased; current laws and regulations at all levels must be improved and harmonized.

How a modern flora can help in identifying potential invasive species

We also should have better tools for recognizing the potential for species to become invasive and to make it easier for scientists and the general public to identify plants and to obtain information about them. Several current flora projects have as their goal the preparation and publication of floras for large, species-rich parts of the northern hemisphere. All are traditional, hard bound, multi volume floras with keys for identification, descriptions for each taxon to aid in identification, habitat and distribution statements, notes on further distinguishing features, comments on taxonomic problems and relationships and discussions of weediness, conservation status and other aspects of the biology of the plants. It seems, however, that we as flora writers are not utilizing to full advantage the technologies and computer resources available to us to produce the most useful floras possible for the 21st century. Powerful small computers that can easily be taken to the field, powerful new database programs, digital cameras, global positioning system receivers (GPS), geographical information systems (GIS), freely accessible modern databases of plant names, and other information about plants, should allow us to gather and disseminate information about the flora of a particular area in new and more convenient ways to far more people than we currently reach. We should be able to make it easier for anyone to pick up a plant in the field and be able to identify it quickly and accurately by using interactive keys that allow the most obvious features of the plant to be scored. We should be providing photographs of the plant, with enlargements of critical features, to confirm the identification.

Kartesz and Meacham (1999) are aiming toward such a system for the next edition of their computerized *Synthesis of the North American Flora*. The second edition will allow input of a number of easily observable characteristics for about 20 morphological features of a plant and thereby reduce the possibility of its identity to a handful of taxa (John Kartesz pers. comm). Those taxa can then be compared to photographs stored in the database, which the computer will display as a series of thumbnails once the number of possibilities has been reduced to a manageable number. The user clicks on a thumbnail to display a larger image for comparison with the plant in hand. The Kartesz and Meacham model, however, will rely solely on morphological information, but an ideal electronic flora should also incorporate

additional information from Global Positioning Systems (GPS) and global information systems (GIS) to make possible not only the identification of a plant, but, for non-native plants, predictions on their potential to spread beyond areas where they first become naturalized. For purposes of this paper the discussion will be restricted to the area covered by the project to prepare the *Flora of North America* (Brouillet and Whetstone 1993), but it could easily apply to any large, discrete region of the world. The *Flora of North America* is a traditional flora that will treat all of the plants of North America north of Mexico plus those of Greenland. The Flora will be published in 30 volumes (hardly a work that can be carried into the field) and include all the flowering plants, ferns, gymnosperms, bryophytes and hepatics. There are roughly 17,000 taxa of flowering plants, ferns and gymnosperms in North America as the continent is defined above, which is a formidable number of species to account for in any type of flora, even an electronic one. More will be said about this below.

A number of rather labor intensive steps will be necessary before a computerized flora can be prepared. First, specimens in herbaria will have to be databased and coordinates of latitude and longitude will have to be provided for every collection site. What will that involve? Holmgren et al. (1990) calculated that there were over 60 million specimens in herbaria in the United States and nearly 7 million specimens in the herbaria of Canada in 1990, plus some additional specimens in the herbarium in Greenland. For herbaria with international projects or interests, and therefore many specimens from outside North America, the percentage of specimens from North America will be something less than 100 percent, although the holdings from North America will almost surely make up the majority. Assuming that another small percentage in each herbarium will lack sufficient label data to allow us to know even roughly where they were collected will reduce the number of specimens to be databased still further. Even so, it is reasonable to assume that at least 50 percent of the specimens in North American herbaria, or more than 33 million specimens, were collected in North American and will contain useful locality information that should be stored in a database. One may ask if the extent of collecting has been uniformly sufficient to provide us with an accurate presentation of distributions. For the most part the answer will be yes. See, for example, the distribution maps of *Phryma leptostachya* (Thieret 1972), *Salix caroliniana* (Argus 1986), *Lyonia lucida* (Judd 1981), *Oenothera argillicola*, *O. oakesiana*, *O. biennis* and *O. villosa* subspp. *villosa* and *strigosa* (Dietrich et al. 1997) and *Alnus viridis* subsp. *crispa* (Furlow 1979), which have ranges that extend over various portions of North America, or the maps in various state atlases and floras, such as those of Albee et al. (1989) for Utah, Great Plains Flora Association (1977) for the Great Plains, Harvill et al. (1992) for Virginia, and Rhodes and Klein (1993) for Pennsylvania. Those examples show that geographical coverage for nearly all plants and for most geographical areas are adequate for databasing and mapping on a continental scale. Many collectors in the past, and many still, fail to record elevation information for their collections. Elevation information can be a very useful aid to identification and every effort should be made to gather and database elevation information for all new collections and, whenever possible, to add elevation information to older collection records when it can be determined unabiguously.

Second, a database or data matrix, of the characters to be used in identification must be created. A sample of such a data matrix is presented in Table 1. To make the database workable, a minimum number of characters

Table 1. Simple data matrix to demonstrate the types of information to be recorded

	Coordinates entered by GPS receiver	**Elevation** entered by GPS receiver	**Duration** annual, biennial, perennial	**Habit** tree, shrub, herb, vine	**Nutrition** autotrophic, saprophytic or parasitic	**Leaves** present, absent, or scale-like	**Leaf position** alternate, opposite, whorled	**Leaf dissection** simple, compound
Species A								
Species B								
Species C								
Species D								
Species E								
Species F								
Species G								

must be used and must be scored for all taxa in the flora area. As much as possible, easily observable features should be chosen and those characters must be scored for all taxa in the flora area. This should not prevent databasing characters that are more difficult to observe, or less diagnostic, and the database should be constructed in such a way to make it possible to enter those characters and character states whenever that information is available.

Morphological information for such a flora of North America is readily obtainable for most taxa in published works, including state and regional floras and monographs and revisions, and often in more general works. For example, works such as Cronquist (1992) can be used to score characters that are uniform throughout a family. For example, habit = trees, leaves = opposite, fruit = winged, etc., for all members of the Aceraceae in North America. Careful thought will have to be given, however, to which characters will be required for all taxa. The character state for each taxon must then be evaluated and scored for all taxa in the flora area. To the extent possible, those characteristics should be easily observable, but highly diagnostic.

For identification purposes, the number of species in the *Flora of North America* area may seem formidable, but the beauty of this system is that it will take advantage of geographic data to narrow the number of possibilities for any particular spot on the continent to a manageable figure connected to a GPS receiver, the first bit of information to be fed into the system will be the geographic coordinates of the point where the user is standing. The system should be designed to make use of electronic gazetteers already available for North America so that once the coordinates are determined, the computer can use that information to determine the county where the user is standing. Many states in the United States, particularly in states east of the Rocky Mountains, have floras or atlases that display distribution of plants at the level of county. Suddenly, with a GPS receiver, an identification system with 17,000 possibilities is reduced to one with a thousand or fewer. The next bit of information, elevation, also entered automatically by the GPS receiver, can reduce the number of possibilities still further for many parts of the continent.

The user should then be presented with a form where easily observable characteristics of the plant can be entered. Several interactive identification systems already exist, the best known of which is the DELTA (DEscriptive Language for TAxonomy) sys-

tem and Intkey (Interactive Key) (Dallwitz 1980, Dallwitz et al. 1993, 1995, 1999, 2000). The user of Intkey is given a list of the most useful characters for identification. By selecting the character and entering the character state, the number of choices is gradually reduced to the one or few taxa that most closely match the features of the information entered. Photographs and other types of images can be stored in DELTA and the user can then click on an image to confirm the identification or to distinguish between several similar taxa. The drawback of DELTA is that it is not integrated with GPS or GIS.

GPS and GIS can be powerful aids in identification and should be incorporated in all new floristic projects. For example, once the number of possible taxa is reduced using a GPS receiver to those within the county where the user is standing, or to within a predetermined radius of the user in parts of North America where counties have not been established, the computer should be able to analyze the information entered by the user to determine how closely it matches information in the database for the taxa known from that county or area. If the comparison of the characters and character states entered by the user provide a good match with information already in the database for one or several taxa already known for that area, a screen of thumbnails will be presented. The user will be able to click on a thumbnail for a larger image, and be provided with enlargements of finer and more critical details, to confirm the identification. If the characters and character states entered by the user do not result in a good match for plants from the place where the user is standing, the computer should be able to recognize that fact and analyze features of plants known to occur in adjacent counties, or from a slightly wider radius, to seek a more exact match. If a good match is still not obtained, the computer should take advantage of GIS to locate the one or few species that most closely match features entered and the ecology and physical features of the site where the user is standing. Using GIS, the computer can search through regions of North America where the geology, soils, climate, rainfall and vegetation patterns and hydrology match the area of the user. By taking advantage of the geographic information available and combining it with information in the database about the plants of the area should make it possible to identify weedy species soon after they move into an area.

Besides its value to professional biologists, a computerized flora using GPS will be particularly attractive to amateur botanists and the general public who will then be able to identify quickly and accurately the plants they find on visits to state and national parks or to other vacation spots. It should be possible for the user to select a particular place, the Great Smoky Mountains National Park, or Organ Pipe Cactus National Monument, for example, and have the computer reduce the number of taxa to be compared to only those known to occur within the area chosen. Instead of the necessity of purchasing a separate guide for each park, or a different field guide for each region of North America, the user will be able to generate a field guide on the spot for the immediate area where he or she is standing. Such a field guide will be more accurate than current field guides, since it will include all the taxa from North America, and it will be possible to focus down to only those known from the area where the user is standing. For example, in a detailed regional field guide to the wildflowers of the eastern United States all the species of goldenrod (*Solidago*) may be shown, each with a very brief description and a generalized distribution map, making it difficult for the casual user to make an accurate identification from the complexity of possible choices. In other field guides it may be that only the common species are shown for the

area covered and the rarer ones left out, thereby leaving the user to wonder if the plant in hand is really what it most closely matches in the field guide or something rare and not included. The computerized field guide not only contains all the species the user of the field guide might find anywhere in North America, but also reduces the number to the usually manageable few that occur within the user's immediate vicinity. The electronic flora should also contain all the colloquial names ever applied to the plants of North America so that a user knowing a common name (or family or genus name) can further reduce the number of possible choices.

It will also be possible with a continent-wide, computerized flora to generate an account of all the plants for a state, province, county, park or any other region the user designates. Such a flora will be of tremendous use to conservationists, government agencies and others interested in rare plants, since it will make it possible to see the distribution of a rare plant for a state, region, country or continent. Currently, states often have lists or red books of the rare plants within their borders, but generally cannot provide a means, other than a brief statement, to easily visualize the broader range of the plants they monitor. Finding that information generally requires consulting numerous floras, reports, red books, etc., most of which are not readily available to those agencies needing the information.

An electronic flora can also be used to track the distribution of plants over time. The electronic flora can be queried to display distribution maps of particular taxa at annual intervals, five year intervals, or intervals of the user's choosing, to track the rate of spread of weedy plants, the contraction in ranges of rare or threatened plants, or the migrations of plants in response to global warming.

How can such an electronic flora be produced? The greatest difficulties in producing such a flora will be in databasing the specimens and entering the information for all the plants in the area to be covered. Finding sufficient funding and the human resources to accomplish the task may seem formidable, but by utilizing already available human resources it might be possible to accomplish the task rather inexpensively and in a relatively short amount of time. There are currently a number of projects underway in North America to produce county, state or regional floras, many of which are knowingly or unknowingly duplicating each other's efforts by gathering the same kinds of information on synonymy, bibliography, plant descriptions, habitats and distributions. If the resources and energy going into these individual projects could be channeled into an international, integrated effort to produce a computerized, information rich, continental flora, the original objectives of the individual projects will still be accomplished, but the participants will be contributing to an effort that will be significantly greater than the sum of the individual parts. Once the information is entered, it will be possible to generate subsets of the continental flora not only for the area of interest to the contributor, but for any part of North America, be it a state, a county, a region or a national or state park.

The electronic flora should be maintained at a central location where taxonomy and nomenclature can be kept current, and it should be available to anyone wishing to use it. It should be accessible for data entry and editing by registered users and it should allow for new records to be added individually or in batches. Once a significant number of records are entered it will be possible for new records to be checked automatically by the computer to determine if they fall within the range of distribution of specimens already entered. If a specimen is recorded as occurring outside the existing range by a predetermined distance, as determined by distance to the next closest collection, the computer will

send up a flag to warn the user that the geographical information or the identification may be incorrect. Besides being a means of preventing the entering of incorrect data, it will highlight significant range extensions and disjunct populations of native plants and provide a warning of alien species significantly expanding their range. The flora should also be downloadable so that users can store it on their own personal desktop computer, or on their hand-held or notebook computer to take it into the field. Updates also should be made available periodically over the Internet.

Some may question whether or not the identifications of specimens in the herbaria of North America should be verified before data entry. The answer is probably no, that to save time they should not be verified in the initial stage of data entry. Again, once a significant number of specimens have been entered it will be possible to present detailed distribution maps where the identities of individual records showing up far outside the range of the taxon can be checked. Besides, probably all rare plants in North America have been examined so thoroughly that there is little likelihood that any remain misidentified (although it is possible some may be hiding under the names of more common species). Misidentifications of widespread common plants will not seriously affect the usefulness of the electronic flora and the records for those specimens can be corrected when their true identities are discovered.

An on-line continental wide flora should not only be useful to amateur and professional botanists in providing solid, detailed, updateable information on the plants of North America, but also be attractive to anyone interested in knowing about the plants they see all around them and being able to take with them into the field the means for allowing them to identify those plants.

I wish to thank Dr. Les Mehrhoff for providing slides and very useful discussions on introduced plants in the New England area, Dr. George Staples for information on introduced plants in the Hawaiian Islands, and especially Dr. Kunio Iwatsuki for inviting me to participate in the symposium on introduced species and for his kind hospitality during my visit to Japan.

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ボフォード D. E.：**導入種と21世紀の植物誌**

環境破壊の主要な原因には生育地破壊，生育地分断，動植物の過剰採取，環境汚染，外来種侵入が含まれる．最初にあげた4原因は，古くから認識されてきたが，外来種侵入については自然環境および人類の福祉と健康に対する深刻な脅威であるということが国際的な規模で受認されるようになったのはごく最近になってである．北米では，エゾミソハギ（*Lythrum salicaria*）のようによく知られていて肉眼でみえるものからコレラ菌（*Vibrio cholelerae*）のように顕微鏡によらなければみえないものまで導入種は多種多様である．ここでは，農業生産性の減少，人類の健康に対する脅威，導入種を制御するための直接の出費に要する経費について論じる．外来植物種の導入を監視し，かつその拡散を予測することに役立つ，植物誌作成にあたっての現代的な手法を紹介する．対話式同定ツール，GIS（地理情報システム），ならびに国や大陸を対象とした植物標本のデジタル画像とそのラベル情報のデータベースは，どの地域のどの植物であってもそれを即座に同定することを可能にするだけでなく，植物の導入を監視し，それらの自然育地への拡散の潜在性を予測する強力な方法を提供することができる．

（ハーバード大学植物標本館）